IfI Technical Reports

Institute of Computer Science,
Clausthal University of Technology

IfI-05-08

Clausthal-Zellerfeld 2005

Intentions and Strategies in Game-Like Scenarios

Wojciech Jamroga[1], Wiebe van der Hoek[2] and Michael Wooldridge[2]

[1]Institute of Computer Science, Clausthal University of Technology, Germany
wjamroga@in.tu-clausthal.de
38 678 Clausthal, Germany
[2]Department of Computer Science, University of Liverpool, UK
Liverpool L69 7ZF, UK
{wiebe,mjw}@csc.liv.ac.uk

Abstract

In this paper, we investigate the link between logics of games and "mentalistic" logics of rational agency, in which agents are characterized in terms of attitudes such as belief, desire and intention. In particular, we investigate the possibility of extending the logics of games with the notion of agents' intentions (in the sense of Cohen and Levesque's BDI theory). We propose a new operator $(\mathbf{str}_a\sigma)$ that can be used to formalize reasoning about outcomes of strategies in game-like scenarios. We briefly discuss the relationship between intentions and goals in this new framework, and show how capture dynamic logic-like constructs can be captured. Finally, we demonstrate how game-theoretical concepts like Nash equilibrium can be expressed to reason about rational intentions and their consequences.

Keywords: multi-agent systems, strategic reasoning, common sense reasoning.

1 Introduction

In this paper, we investigate the link between logics of games (in particular, ATL – the temporal logic of coalitional strategic ability) and "mentalistic" logics of rational agency, in which agents are characterized in terms of attitudes such as belief, desire and intention. It is our contention that successful knowledge representation formalisms for multi-agent systems would ideally embrace both traditions. Specifically, we propose to extend ATL with agents' intentions (in the sense of Cohen and Levesque's BDI theory) in order to reason about agents' intended actions and their consequences.

This is especially interesting in game-like situations, where agents can consider hypothetical strategies of other agents, and come up with a better analysis of the game. We define counterfactual operator $(\mathbf{str}_a\sigma)$ to reason about outcomes of such strategies; in consequence, one can reason explicitly about *how* agents can achieve their goals, besides reasoning about *when* does it happen and *who* can do it, inherited from temporal logic and logic of strategic ability. We briefly discuss the notion of intending *to do* an action, as opposed to of intending *to be* in a state that satisfies a particular property; we analyze the relationship between action- and state-oriented intentions, and point out that our framework allows for a natural interpretation of *collective* intentions and goals. We show how a dynamic-like logic of strategies can be defined on top of the resulting language, and argue that propositional dynamic logic can be embedded in it in a natural way. We present a model checking algorithm that runs in time linear in the size of the model and length of the formula. Finally, we suggest that this operator sits very well in game-like reasoning about rational agents, and show examples of such reasoning.

The inspiration comes from various sources: folk psychology (the BDI architecture of *beliefs*, *desires* and *intentions*), logics of time (temporal logic), knowledge (epistemic logic) or obligations (deontic logic), logics of programs (dynamic logic), theories of rational behavior (game theory) etc. Obviously, no formal theory of agency can explain *all* relevant aspects of a multi-agent system in *all* possible contexts. Such theories, however, play an important role in explaining the behavior of systems (and their components) with notions that are both formal (which enables further formal investigation) and fit human "commonsense" understanding of the world.

2 What Agents Can Achieve

In this section, we discuss several aspects of agents acting in game-like scenarios. First of all, we introduce Alternating-time Temporal Logic that allows one to reason about what agents can achieve with their strategies.

2.1 Strategic Abilities: ATL

Alternating-time Temporal Logic (ATL) [1, 2, 3] is a generalization of the branching time temporal logic CTL [7, 10, 9], in which path quantifiers are replaced by *cooperation modalities*. Formula $\langle\langle A\rangle\rangle\varphi$, where A is a coalition of agents (i.e., a subset of the "grand" set of agents $\mathbb{A}\mathrm{gt}$), expresses that there exists a collective plan for A such that, by following this plan, A can enforce φ. ATL formulae include temporal operators: "$\bigcirc$" ("in the next state"), $\Box$ ("always") and $\mathcal{U}$ ("until").[1] Every occurrence of a temporal operator is preceded by exactly one cooperation modality in ATL (which is sometimes called "vanilla" ATL). The broader language of ATL*, in which no such restriction is imposed, is not discussed here. It is worth pointing out that the extension of ATL, proposed in this paper, makes use of terms that describe strategies, and in this sense is very different from ATL, in which strategies appear only in the semantics and are *not* referred to in the object language. We will introduce the semantic concepts behind ATL formally in Section 3. For now, we give a flavor of it with the following example.

[1] Additional operator $\Diamond$ ("now or sometime in the future") can be defined as , $\Diamond\varphi \equiv \top\,\mathcal{U}\varphi$.

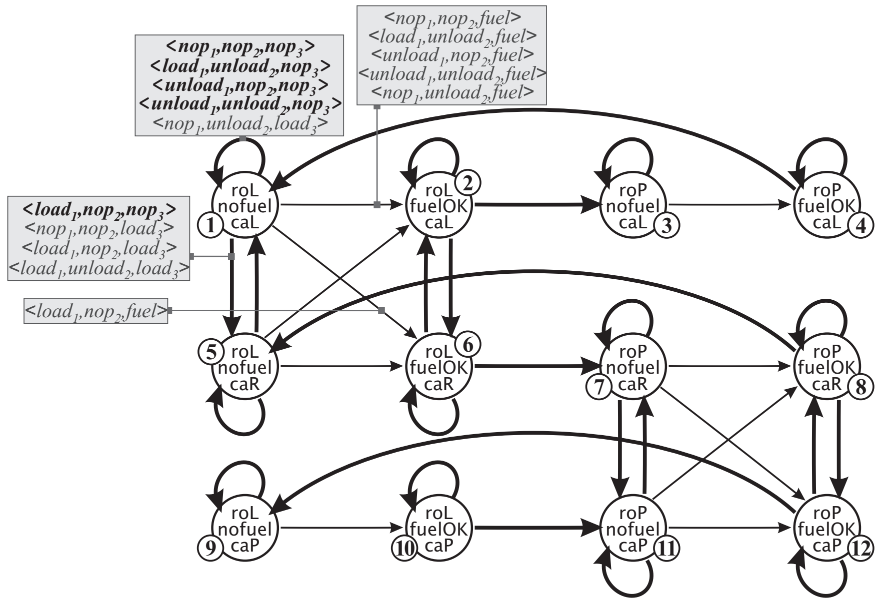

Figure 1: Simple Rocket Domain. The "bold" transitions are the ones in which agent 3 intends to always choose nop_3.

Example 1 Consider a modified version of the Simple Rocket Domain from [5]. There is a rocket that can be moved between London (roL) and Paris (roP), and piece of cargo that can lie in London (caL), Paris (caP), or inside the rocket (caR). Three agents are involved: 1 who can load the cargo, unload it, or move the rocket; 2 who can unload the cargo or move the rocket, and 3 who can load the cargo or supply the rocket with fuel. Every agent can also stay idle at a particular moment (the nop – "no-operation" actions). The "moving" action has the highest priority. "Loading" is effected when the rocket does not move and more agents try to load than to unload; "unloading" works in a similar way (in a sense, the agents "vote" whether the cargo should be loaded or unloaded). Finally, "fueling" can be accomplished only when the rocket tank is empty (alone or in parallel with loading or unloading). The rocket can move only if it has some fuel (fuelOK), and the fuel must be refilled after each flight. A model for the domain is shown in Figure 1 (we will refer to this model as M_1). All the transitions for state 1 (the cargo and the rocket are in London, no fuel in the rocket) are labeled; output of agents' choices for other states is analogous.

Example ATL formulae that hold in $M_1, 1$ are: $\neg\langle\langle 1\rangle\rangle\Diamond\mathsf{caP}$ (agent 1 cannot deliver the cargo to Paris on his own), $\langle\langle 1,3\rangle\rangle\Diamond\mathsf{caP}$ (1 and 3 can deliver the cargo if they cooperate), and $\langle\langle 2,3\rangle\rangle\Box(\mathsf{roL} \wedge \langle\langle 2,3\rangle\rangle\Diamond\mathsf{roP})$ (2 and 3 can keep the rocket in London forever, and at the same time retain the ability to change their strategy and move the rocket to Paris). ■

2.2 Between Utilities and Actions

Players' strategies and players' preferences are key concepts in game theory. Utility functions are used to model players' preferences in game theory. A rational agent, it is argued, should act so that his utility is maximal in the long run. Preference Game Logic (PGL) [25] has been an attempt to import the concept of preferences into the framework of ATL via operator $[A : p]$, meaning that "*if agents A prefer outcome p then formula φ holds*". Semantically, PGL interprets preference "$A : p$" with a predefined utility vector for A; at the same time, the rest of agents ($\mathbb{A}\mathrm{gt} \setminus A$) are assigned the opposite payoff vector. The resulting game is used to find all the Nash equilibria; finally, we collect all the agents' choices (not strategies!) that appear in any equilibrium, and we throw away other actions from the model. Then, $[A : p]\varphi$ holds iff φ is true in the resulting model. The intuition behind this construction is that Nash equilibria generate the choices that a rational player may choose, hence we get rid of the other choices from the model, since our players (being presumably rational) will never use them. We would like to follow the basic idea behind PGL in this paper; however, it models agents' behavior in a rather arbitrary way. The game that defines the semantics of $[A : p]\varphi$ is arbitrary, and the zero-sum game assumption that if A prefer p then $\mathbb{A}\mathrm{gt} \setminus A$ prefer $\neg p$ is one we would like to avoid. Nash equilibrium is only one of several alternative rationality criteria (like dominant strategies, Pareto efficiency etc.), and assuming that *all* the players are rational restricts the applicability of the logic.

So, *what are preferences/utilities for in game theory?* Basically, their purpose is to imply the "optimal" decision. For an agent in a game, *his* utility function should help him realize which choice is the best for him. Moreover (what is more important here), analyzing utility functions *of the opponents* helps the agent to predict their strategies, which is crucial since the outcome of his choices depends on the opponents' strategies heavily. In a word: one needs to know players' choices (strategies) in order to reason about the game more precisely. If one can know (or assume) that player b is going to use strategy s_b throughout the game (for instance, we assume that b is a rational player in some sense, and s_b is the optimal strategy in this sense) then he can propose a finer analysis of the game, and adapt his resulting strategy to the fact (or assumption). We believe that this kind of reasoning can be split into two separate concepts:

1. *suppose that agents A are rational and prefer particular outcomes, then they should/may play strategy S_A;*
2. *suppose that A intend to play strategy S_A, then φ holds*.

In this paper, we focus mainly on reasoning about outcomes of strategies, regardless of where the strategies come from (and whether they are rational or not). We formalize this kind of reasoning in section 3. Moreover, having a device for reasoning about outcomes of *all* strategies, and a criterion of rationality, we can combine the two to reason about outcomes of strategies that *rational* agents may or should follow. This issue is discussed in more detail in Section 4.

3 ATL with Intentions

The language of ATL+I (with respect to a set of agents $\mathbb{A}\mathrm{gt}$, atomic propositions Π, and sets of primitive strategic terms $\Upsilon_{a_1}, ..., \Upsilon_{a_k}$ for agents $a_1, ..., a_k$ from $\mathbb{A}\mathrm{gt}$) can be formally defined as the following extension of ATL:

$$\varphi ::= p \mid \neg\varphi \mid \varphi \land \varphi \mid \langle\langle A\rangle\rangle \bigcirc \varphi \mid \langle\langle A\rangle\rangle \Box\varphi \mid \langle\langle A\rangle\rangle \varphi \mathcal{U} \varphi \mid (\mathbf{str}_a \sigma_a)\varphi$$

where $p \in \Pi$ is a proposition, $a \in \mathbb{A}\mathrm{gt}$ is an agent, $A \subseteq \mathbb{A}\mathrm{gt}$ is a group of agents, and $\sigma_a \in \Upsilon_a \cup \{\,\mathsf{any}\,\}$ is a strategic term for a.[2]

Models for ATL+I extend *concurrent game structures* from [3] with intention-accessibility relations, strategic terms and their denotation, and can be defined as:

$$M = \langle \mathbb{A}\mathrm{gt}, Q, \Pi, \pi, Act, d, o, \mathcal{I}_{a_1}, ..., \mathcal{I}_{a_k}, \Upsilon_{a_1}, ..., \Upsilon_{a_k}, [\![]\!]_{a_1}, ..., [\![]\!]_{a_k}\rangle.$$

$\mathbb{A}\mathrm{gt} = \{a_1, ..., a_k\}$ is the set of all agents (the "grand coalition"), Q is the set of states of the system, Π the set of atomic propositions, $\pi : \Pi \to \mathcal{P}(Q)$ a valuation of propositions, and Act the set of (atomic) actions; function $d : \mathbb{A}\mathrm{gt} \times Q \to \mathcal{P}(Act)$ defines actions available to an agent in a state, and o is the (deterministic) transition function that assigns the outcome state $q' = o(q, \alpha_1, \ldots, \alpha_k)$ to every state q and tuple of actions $\langle \alpha_1, \ldots, \alpha_k\rangle$ that can be executed by the grand coalition in q.

$\mathcal{I}_a \subseteq Q \times Act$ is the intention-accessibility relation of agent a ($q\mathcal{I}_a\alpha$ meaning that a possibly intends to do action α when in q). A *strategy* of agent a is a conditional plan that specifies what a is going to do in every possible situation (state). We represent a's strategies as functions of type $s_a : Q \to \mathcal{P}(Act)$ such that, for every $q \in Q$:

1. $s_a(q)$ is non-empty, and
2. $s_a(q) \subseteq d_a(q)$.

Thus, strategies can be non-deterministic – we only require that they specify choices of agents, and at least one choice per state. Strategic terms $\sigma \in \Upsilon_a$ are interpreted as strategies according to function $[\![]\!]_a : \Upsilon_a \to (Q \to \mathcal{P}(Act))$ such that $[\![\sigma]\!]_a$ is a valid strategy for a. We also define $[\![\,\mathsf{any}\,]\!]_a$ as the strategy that collects all valid actions of a, i.e. $[\![\,\mathsf{any}\,]\!]_a(q) = d_a(q)$ for every q. A *collective strategy* for a group of agents $A = \{a_1, ..., a_r\}$ is simply a tuple of strategies $S_A = \langle s_{a_1}, ..., s_{a_r}\rangle$, one per agent from A. A *path* $\Lambda = q_0q_1q_2...$ in M is an infinite sequence of states that can be effected by subsequent transitions, and refers to a possible course of action (or a

[2] In fact, to be formally correct, a and A should be also defined as an agent term and a coalitional term, respectively, to distinguish between the syntactical symbols and their semantic denotations (i.e. agents and their sets).

possible computation) that may occur in the system. We define $\Lambda[i]$ to be the ith state in path Λ.

In ATL, agents can choose any legal action at each state. Having added intentions to ATL models, we assume that *agents only do what they intend*. We say that strategy s_a is *consistent with a's intentions* if the choices specified by s_a are never ones that a does *not* intend, i.e. $q\mathcal{I}_a\alpha$ for every q and $\alpha \in s_a(q)$. A collective strategy S_A is consistent with A's intentions if s_a are consistent with a's intentions for all $a \in A$. The set of outcome paths of a (collective) strategy S_A from state q, denoted by $out(q, S_A)$, is defined as the set of paths in M, starting from q, that can result from A executing S_A. Unlike in ATL, we are going to consider only courses of action that are consistent with intentions of all agents:

$out(q, S_A) = \{\Lambda = q_0q_1... \mid q_0 = q$ and for every $i = 1, 2, ...$ there exists a tuple of all agents' decisions $\langle\alpha^{i-1}_{a_1}, ..., \alpha^{i-1}_{a_k}\rangle$ such that $q_{i-1}\mathcal{I}_a\alpha^{i-1}_a$ for $a \in \mathbb{A}\mathrm{gt}$, and $\alpha^{i-1}_a \in s_a(q_{i-1})$ for $a \in A$, and $o(q_{i-1}, \alpha^{i-1}_{a_1}, ..., \alpha^{i-1}_{a_k}) = q_i\}$.

Semantics of ATL+I can be given via the following clauses:

$M, q \models p$ iff $q \in \pi(p)$, for an atomic proposition p;

$M, q \models \neg\varphi$ iff $M, q \not\models \varphi$;

$M, q \models \varphi \wedge \psi$ iff $M, q \models \varphi$ and $M, q \models \psi$;

$M, q \models \langle\langle A\rangle\rangle\bigcirc\varphi$ iff there is a collective strategy S_A consistent with A's intentions, such that for every $\Lambda \in out(q, S_A)$, we have that $M, \lambda[1] \models \varphi$;

$M, q \models \langle\langle A\rangle\rangle\Box\varphi$ iff there is S_A consistent with A's intentions, such that for every $\Lambda \in out(q, S_A)$ and $i = 0, 1, 2, ...$, we have $M, \lambda[i] \models \varphi$;

$M, q \models \langle\langle A\rangle\rangle\varphi\mathcal{U}\psi$ iff there is S_A consistent with A's intentions, such that for every $\Lambda \in out(q, S_A)$ there is $i \geq 0$ such that $M, \Lambda[i] \models \psi$ and for all j such that $0 \leq j < i$, we have $M, \Lambda[j] \models \varphi$;

$M, q \models (\mathbf{str}_a\sigma)\varphi$ iff $revise(M, a, [\![\sigma]\!]_a), q \models \varphi$.

Function $revise(M, a, s)$ updates model M by setting a's intention-accessibility relation $\mathcal{I}_a = \{\langle q, \alpha\rangle \mid \alpha \in s(q)\}$, so that s and $\mathcal{I}_a$ represent the same mapping in the resulting model. In a way, $revise$ implements agents' intention revision (or strategy change) in game structures with intentions.

Example 2 Let us go back to the rocket agents from Example 1. If we have no information about agents' intended actions and strategies, we can model the game with model M_1' which augments M_1 with the least restrictive intention-accessibility relations, so that $q\mathcal{I}_a\alpha$ for every $q \in Q$, $a \in \mathbb{A}\mathrm{gt}$ and $\alpha \in d_a(q)$. Let nop denote the "lazy" strategy for agent 3, i.e. $[\![nop]\!]_3(q) = nop_3$ for every q. Model $M_2 = revise(M_1', 3, [\![nop]\!]_3)$ depicts the situation where 3 intends to play nop and the other players have no specific intentions. Transitions, consistent with the intention-accessibility relations, are indicated with bold face font and thick arrows in Figure 1.

Note that, for example, $M_2, 1 \models \langle\langle 2 \rangle\rangle \Box \neg \mathsf{caR}$ (agent 2 can keep the cargo outside the rocket), and $M_2, 1 \models \langle\langle\rangle\rangle \Box \mathsf{nofuel}$ (the rocket tank is always empty for all courses of action).[3] Thus, also $M_1', 1 \models (\mathbf{str}_3 nop)\langle\langle 2 \rangle\rangle \Box \neg \mathsf{caR}$ and $M_1', 1 \models (\mathbf{str}_3 nop)\langle\langle\rangle\rangle \Box \mathsf{nofuel}$. ■

The concept of keeping agents' current strategies in the model resembles to some extent the semantics of epistemic temporal strategic logic from [24]. Here, we introduce the strategies into models in the form of modal relations; there, ATL-like formulae are interpreted over models *and* strategies. However, the strategies in [24] are used mostly as a technical device to define the semantics of cooperation modalities: they cannot be referred to in the object language of ETSL, and they change only in a very limited way on the semantic side.

The counterfactual intention operator $(\mathbf{str}_a \sigma)$, on the other hand, is very similar to the commitment operator from [22]. However, committing to a strategy is modeled in [22] through an update operator that changes the temporal structure of the system directly, and hence refers to *irrevocable* commitments. Here, intended strategies can be freely revised or revoked, which makes our proposal close to Stalnaker's work on hypothetical reasoning about strategies [21].

In ATL+I, actions and strategies can be specified as non-deterministic, which has two alternative commonsense interpretations:

1. *genuine non-determinism:* agents are allowed to execute nondeterministic choices, or at least they may not know exactly which action they are going to execute until the very last moment;
2. *underspecification:* the model in general does not specify precisely the exact intentions of agents, but includes all the choices *possibly* intended by them. In principle, there may be no "omniscient observer" as far as agents' actual intentions are concerned.

Remark 1 Our semantics of cooperation modalities deviates from the original semantics of ATL [3] in two respects. First, we employ "memoryless" strategies in this paper, while in [3] strategies assign agents' choices to *sequences* of states (which suggests that agents can recall the whole history of the game). It should be pointed out that both types of strategies yield equivalent semantics for "vanilla" ATL, although the choice of one or another notion of strategy affects the semantics (and complexity) of the full ATL* and most ATL variants for games with incomplete information [20]. Thus, we use memoryless strategies to increase the simplicity and extendability of our approach.

Second, we allow for non-deterministic strategies here for the sake of generality, while only deterministic strategies are used in [3]. We consider non-deterministic strategies vital for modeling situations in which some agents may play at random (inherent

[3] The "empty set" cooperation modality $\langle\langle\rangle\rangle$ is equivalent to the CTL's "for every path" quantifier A. Similarly, $\langle\langle \mathbb{A}\mathrm{gt} \rangle\rangle$ is equivalent to the CTL's "there is a path" quantifier E.

nondeterminism)[4] or we have only partial information about agents' intentions (underspecification). Note that, if agents A have a non-deterministic strategy S_A to guarantee φ *for all computations that may result from playing* S_A, then every deterministic substrategy of S_A guarantees φ as well. In consequence, non-deterministic strategies do not change the semantics of cooperation modalities (even for ATL*). ■

It might be convenient to add collective strategies to the language of ATL+I. For $A = \{a_1, ..., a_r\}$, we define:

$$(\mathbf{str}_A\langle\sigma_{a_1}, ..., \sigma_{a_r}\rangle)\varphi \equiv (\mathbf{str}_{a_1}\sigma_{a_1})...(\mathbf{str}_{a_r}\sigma_{a_r})\varphi.$$

In what follows, we will sometimes overload the symbol any to denote a tuple of strategies $\langle \mathsf{any}, ..., \mathsf{any}\rangle$.

Remark 2 ATL+I semantically subsumes the original "pure" ATL from [3], as ATL models can be treated as a special case of ATL+I models, in which every available choice is possibly intended by agents at each state. ■

Remark 3 ATL+I syntactically subsumes ATL, as the ATL cooperation modalities can be expressed in ATL+I with $(\mathbf{str}_{\mathbb{A}\mathrm{gt}}\ \mathsf{any})\langle\langle A\rangle\rangle\bigcirc\varphi$, $(\mathbf{str}_{\mathbb{A}\mathrm{gt}}\ \mathsf{any})\langle\langle A\rangle\rangle\Box\varphi$, and $(\mathbf{str}_{\mathbb{A}\mathrm{gt}}\ \mathsf{any})\langle\langle A\rangle\rangle\varphi\,\mathcal{U}\,\psi$ respectively. ■

3.1 Intentions *to do* vs. Intentions *to be*

There is an interesting plot in the research on deontic logic (the logic of norms and obligations) [15]. The logic started as a fairly standard modal logic, with the deontic operator $\mathcal{O}$ operating on properties of states ($\mathcal{O}\varphi$: "it ought to be that φ"), and the deontic accessibility relation between states ($q_1\mathcal{R}q_2$: "q_2 is considered correct when being in q_1") [26]. After many years of struggling with anomalies, [14] managed to get rid of most of them by proposing different *substance* of obligations. Namely, that obligations may as well be understood as referring to actions, yielding operator $\mathcal{O}\alpha$ ("action α is obligatory"). This shows that we can have two fundamentally different readings of the modality, both in fact used in the natural language:

- $\mathcal{O}\varphi$: obligation to *be* (in a state that satisfies φ),
- $\mathcal{O}\alpha$: obligation to *do* (action α).

In this paper – among other issues – we consider a particular notion of *intentions*, and a similar remark applies here. Most models from the classical literature on intentions [6, 18, 19, 27] suggest that intentions refer to properties of *situations*, i.e. agents intend to *be* in a state that satisfies a particular property. However, another notion of "intending" seems to be equally common in everyday language (and even in papers that refer to

[4]This interpretation makes nondeterministic strategies similar to *mixed strategies* from game theory. However, we do not assume any probability distribution for the agents' choices here.

agents from a more practical perspective, e.g. [17]): namely, an agent may intend to *do* a particular action or execute a plan. In fact, "intending to do" was already considered in [8]; however, in that work, intentions were treated as a secondary notion that had to be derived from primitive concepts like beliefs or desires. We propose to model these "dynamically-oriented" intentions as first-class entities instead. Having the intentions "to do" in the models, we can also enable reasoning about them in the object language via another modal operator Int_a with the following semantics:

$$M, q \models \mathsf{Int}_a\sigma \textit{ iff for each } \alpha \in Act \textit{ we have } q\mathcal{I}_a\alpha \textit{ iff } \alpha \in [\![\sigma]\!]_a(q).$$

Collective intentions can be defined as:

$$\mathsf{Int}_{\{a_1,\dots,a_r\}}\langle\sigma_{a_1},\dots,\sigma_{a_r}\rangle \equiv \mathsf{Int}_{a_1}\sigma_{a_1} \wedge \dots \wedge \mathsf{Int}_{a_r}\sigma_{a_r}.$$

Furthermore, intentions "to be" can be defined as follows. Let us assume that nondeterministic strategies model *genuine non-determinism* of agents, i.e. that, if $q\mathcal{I}_a\{\alpha_1, \alpha_2, \dots\}$ then agent a does not know himself whether he is going to execute α_1 or α_2 or ... etc. in state q. Under this interpretation, we propose the following definition of coalition A's intentions "to be" (we call such intentions *goals* after Cohen and Levesque):

$$\mathsf{Goal}_A\varphi \equiv (\mathbf{str}_{\mathbb{A}\mathrm{gt}\setminus A}\ \mathsf{any}\,)\langle\!\langle\rangle\!\rangle\varphi.$$

That is, A intend to bring about goal φ iff φ is an inevitable consequence of A's intended strategy, regardless of what other agents do. Note that, in the above definition, φ is a property of paths (courses of action) rather than states. Thus, Goal_a says which courses of action a intends to take part in (or bring about), rather than which states he intends to be in. This approach allows us to express subtle differences between various types of an agent's intentions "to be": the agent may intend to be in a state that satisfies φ right in the *next* moment ($\mathsf{Goal}_a\bigcirc\varphi$), or he may intend to *eventually* bring about such a state ($\mathsf{Goal}_a\Diamond\varphi$), or be in "safe" states all the time ($\mathsf{Goal}_a\Box\mathsf{safe}$) etc. For instance, the "lazy" strategy of agent 3 in model M_2 (Example 2) implies that the rocket will never get out from London if 1 is the initial state – regardless of what 1 and 2 do. Thus, $M_2, 1 \models \mathsf{Goal}_3\Box\mathsf{roL}$.

Nondeterminism of a strategy can have another commonsense interpretation, namely *underspecification* (i.e., $\mathcal{I}_a$ includes all the choices *possibly* intended by a). Then, a's actual intentions can be more specific than the strategy implied by $\mathcal{I}_a$, and we can only deduce *possible goals* of A from A's intention-accessibility relations:

$$\mathsf{PossGoal}_A\varphi \equiv (\mathbf{str}_{\mathbb{A}\mathrm{gt}\setminus A}\ \mathsf{any}\,)\langle\!\langle A\rangle\!\rangle\varphi.$$

Remark 4 It seems worth pointing out that the existing work on the formalization of agents' mental states (BDI) deals only with single-agent intentions. By defining intentions and goals on top of ATL, where *coalition* is a key concept, reasoning about *collective* goals and intentions becomes natural as well. ■

3.2 A Dynamic Logic of Strategies

It should be easy to see from previous examples how we can reason about outcomes of agents' strategies with ATL+I. We point out that our $(\mathbf{str}_a\sigma)$ operator can be used to facilitate reasoning about strategies in the style of dynamic logic [12]. In particular, formulae $[A/\sigma]\varphi$ meaning that *"every execution of strategy σ by agents A guarantees property φ"*, or, more precisely, *"for every execution of strategy σ by A, φ inevitably holds (regardless of what other agents do)"* can be defined as:

$$[A/\sigma]\varphi \equiv (\mathbf{str}_a\sigma)(\mathbf{str}_{\mathbb{A}\mathrm{gt}\setminus A}\,\mathsf{any}\,)\langle\!\langle\rangle\!\rangle\varphi.$$

Note that, in that case, φ should be a temporal formula (path formula), as execution of a strategy is a process that happens over time.

Moreover, we observe that dynamic logic's *programs* are represented with semantic structures of the same kind as strategies, and a fragment of propositional dynamic logic can be embedded in ATL+I with the following definitions, where σ is an atomic program executed by the sole agent $\mathbf{s}$ (the *system*):

$$\begin{aligned} [\sigma]\varphi &\equiv [\mathbf{s}/\sigma]\bigcirc\varphi, \text{ and consequently} \\ <\sigma>\varphi &\equiv \neg[\mathbf{s}/\sigma]\bigcirc\neg\varphi. \end{aligned}$$

A richer language of strategic terms is needed to embed the full syntax of PDL in ATL+I.

We have already pointed out that strategies in ATL are very similar to the way in which programs (or actions) are modeled in dynamic logic. In fact, our strategic terms and their denotations can refer to both strategies and actions. The difference lies not in the semantic representation of actions vs. strategies, but in the way their execution is understood: actions are one-step activities, while a strategy is executed indefinitely (or until it is replaced with another strategy). Our intention modality $\mathsf{Int}_a\sigma$ refers to *actions* that may be played by a in the next step; the counterfactual operator $(\mathbf{str}_a\sigma)$ assigns a *strategy* to a.

3.3 Properties of Intention Revision in ATL+I

Proposition 5 *Let φ be a formula of ATL+I, and let $\mathbf{Ph} \equiv (\mathbf{str}_{\mathbb{A}\mathrm{gt}}\,\mathsf{any}\,)$ be a shorthand for the counterfactual operator that yields the bare, "physical" system without any specific intentions assumed. The following formulae are tautologies of ATL+I:*

1. $(\mathbf{str}_a\sigma_1)(\mathbf{str}_a\sigma_2)\varphi \leftrightarrow (\mathbf{str}_a\sigma_2)\varphi$*: a new intention cancels the former intention.*
2. $(\mathbf{Ph}\langle\!\langle\rangle\!\rangle\bigcirc\varphi) \rightarrow (\mathbf{str}_a\sigma)\langle\!\langle\rangle\!\rangle\bigcirc(\mathbf{Ph}\varphi)$, $(\mathbf{Ph}\langle\!\langle\rangle\!\rangle\Box\varphi) \rightarrow (\mathbf{str}_a\sigma)\langle\!\langle\rangle\!\rangle\Box(\mathbf{Ph}\varphi)$, *and* $(\mathbf{Ph}\langle\!\langle\rangle\!\rangle\varphi\,\mathcal{U}\,\psi) \rightarrow (\mathbf{str}_a\sigma)\langle\!\langle\rangle\!\rangle(\mathbf{Ph}\varphi)\,\mathcal{U}(\mathbf{Ph}\psi)$.
3. $(\mathbf{str}_a\sigma)\langle\!\langle\mathbb{A}\mathrm{gt}\rangle\!\rangle\bigcirc(\mathbf{Ph}\varphi) \rightarrow (\mathbf{Ph}\langle\!\langle\mathbb{A}\mathrm{gt}\rangle\!\rangle\bigcirc\varphi)$*, and similarly for $\Box\varphi$ and $\varphi\,\mathcal{U}\,\psi$.*

The counterfactual operator $(\mathbf{str}_A\sigma)$ is based on model update, which makes it similar to the preference operator from [25] and the commitment operator from [22]. Unlike in those approaches, however, model updates in ATL+I are *not* cumulative (cf. Proposition 5.1). This is because the choices we assume unintended by a via $(\mathbf{str}_a\sigma)$ are not removed from the model, they are only left "unmarked" by the new intention-accessibility relation $\mathcal{I}_a$. The update specified by $(\mathbf{str}_a\sigma)$ does not change the "hard", temporal structure of the system, it may only change the "soft" modal relations that encode agents' mental attitudes. In a way, it makes it possible to distinguish between the "physical" abilities of agents, and their intentional stance. Two important properties of such non-cumulative model updates are addressed by Propositions 5.2 and 5.3: first, a property that holds in the next moment for all *physical* paths of a system, is also *physically* true in the next moment for the paths consistent with agents' intentions; second, if there is an intentionally possible path along which ϕ holds physically in the next moment, then such a path exists in the system physically as well. Similar results hold for other temporal operators. We note that properties 5.2 and 5.3 are analogues of Lemma 1 from [23] and Proposition 2 from [22], but it is not necessary to restrict their scope to universal (resp. existential) formulae in ATL+I (i.e., in a framework with revocable updates).

An interesting kind of property that can be expressed in ATL+I is: $(\mathbf{str}_A\sigma)\langle\!\langle\rangle\!\rangle\Box(\varphi \wedge (\mathbf{str}_A\ \mathsf{any})\langle\!\langle A\rangle\!\rangle\Diamond\neg\varphi)$: agents A can use strategy σ to enforce that always φ, and at the same time retain *physical* ability to falsify φ. For instance, for our rocket agents, we have that $M_2, 1 \models (\mathbf{str}_{2,3}\langle nop_2, nop_3\rangle)\langle\!\langle\rangle\!\rangle\Box(\mathsf{roL}\wedge(\mathbf{str}_{2,3}\ \mathsf{any})\langle\!\langle 2,3\rangle\!\rangle\Diamond\mathsf{roP})$. Note that this kind of property cannot in general be expressed if models are updated by removing transitions.

ATL+I makes it also possible to discuss the dynamics of intentions: we can consider what happens if some agents change their strategies after some time. For example, formula $(\mathbf{str}_b\sigma_1)\langle\!\langle\rangle\!\rangle\Diamond(\mathbf{str}_b\sigma_2)\langle\!\langle\rangle\!\rangle\Diamond\varphi$, says that φ must be eventually achieved if agent b starts with playing strategy σ_1, but after some time switches to σ_2. Another formula, $(\mathbf{str}_b\sigma_1)\langle\!\langle a\rangle\!\rangle\Diamond((\mathbf{str}_b\ \mathsf{any})\langle\!\langle a\rangle\!\rangle\Box\varphi)$, states that, if b plays σ_1 initially, then a can secure φ afterwards, even if b changes his strategy. (Example: if b refrains from selling his assets of company a for some time, then a can keep away from bankruptcy, regardless of what b decides to do when a's recovery plan has been executed.)

Finally, the following formulae are tautologies of ATL+I too:

Proposition 6

1. $(\mathbf{str}_a\sigma)\mathsf{Int}_a\sigma$. *This one can be strengthened to* $(\mathbf{str}_a\sigma)\langle\!\langle\rangle\!\rangle\Box\mathsf{Int}_a\sigma$*: under the assumption that* a *intends to play* σ, a *will play* σ *in any reachable state.*
2. $(\mathbf{str}_{a_1}\sigma_1)(\mathbf{str}_{a_2}\sigma_2)\varphi \equiv (\mathbf{str}_{a_2}\sigma_2)(\mathbf{str}_{a_1}\sigma_1)\varphi$ *for* $a_1 \neq a_2$*: reasoning about different agents' intentions is commutative.*

3.4 Model Checking and Planning with ATL+I

The *model checking problem* for ATL+I is the problem of determining, for any given ATL+I formula φ, model M, and state q in M, whether or not $M, q \models \varphi$. The importance of model checking has three reasons. First, in many real-life situations, it is relatively easy to come up with a "natural" model of the reality. Next, checking if a property holds in a given model is computationally less expensive than checking if it holds in *all* models– thus, model checking is often tractable in the cases where other "canonical" problems (like satisfiability checking or theorem proving) are not. Finally, the idea of "planning as model checking" [11] gives it a practical flavor: model checking algorithms can be adapted for generating plans in various domains.

The following algorithm extends the ATL model checking algorithm from [3] to compute the set of states Q_φ in which φ holds in M.

- Cases $\varphi \equiv p, \neg\psi, \psi_1 \wedge \psi_2$: tackle in the standard way.
- Case $\varphi \equiv (\mathbf{str}_a \sigma)\psi$: compute $M' = revise(M, a, [\![\sigma]\!]_a)$, and check ψ in M'.
- Case $\varphi \equiv \langle\langle A \rangle\rangle \bigcirc \psi$: compute Q_ψ for the *original* model M, then go through M deleting transitions where any agent a performs an action not dictated by $\mathcal{I}_a$. Finally, use the ATL model checking algorithm for formula $\langle\langle A \rangle\rangle \bigcirc Q_\psi$ and the resulting ("trimmed") model.
- Cases $\varphi \equiv \langle\langle A \rangle\rangle \Box \psi$, $\langle\langle A \rangle\rangle \psi_1 \mathcal{U} \psi_2$: analogous.

Let us observe that given M, a, and σ, computing $revise(M, a, s_a)$ and the "trimming" procedure can be done in time $O(m)$, where m is the number of transitions in M. As ATL model checking enjoys complexity of $O(ml)$, it gives us the following result.

Proposition 7 *Model checking an* ATL+I *formula φ in model M can be done in time $O(ml)$, where m is the number of transitions in M, and l is the length of φ.*

Note that the ATL planning algorithm from [13] can be easily extended to handle strategic planning in the presence of intentions.

4 Reasoning about Rational Intentions

Using the counterfactual operator $(\mathbf{str}_A \sigma)$, we do not assume anything about payoffs and/or preferences of players, about their rationality, optimality of their decisions etc. – we simply assume that A intend to play σ (for whatever reasons), and ask what are the consequences. Reasoning about *rational* agents can be done on top of this: we should define what it means for an intention to be rational and then reason about outcomes of such intentions with $(\mathbf{str}_A \sigma)$.

ATL operators $\langle\langle A \rangle\rangle$ can be seen as a formalization of reasoning about *extensive game forms* – and concurrent game structures can be seen as a generalization of traditional game trees with perfect information, except for agents' utilities (concurrent game structures may include cycles and simultaneous moves of players, which are absent in game trees). In order to "emulate" utilities, we follow the approach of [4]. Let U denote the set of all possible utility values in the game; U will be fixed and finite for any given game. For each value $v \in U$ and agent $a \in \mathbb{A}\mathrm{gt}$, we introduce a proposition $(u_a \geq v)$ into our set Π of primitive propositions, and fix the valuation function π so that $(u_a \geq v)$ is satisfied in state q iff a gets at least v in q. The correspondence between a traditional game tree Γ and a concurrent game structure M can be captured as follows. Let $\Gamma = \langle \Sigma, \mathcal{A}, H, ow, u \rangle$, where Σ is a finite set of players, $\mathcal{A}$ a finite set of actions, H a finite set of (finite) action sequences (i.e. legal game histories), and $ow(h)$ defines which player "owns" the next move after history h. We define the set of actions available at h as $\mathcal{A}(h) = \{\alpha \mid h\alpha \in H\}$, and the set of terminal situations as $Term = \{h \mid \mathcal{A}(h) = \varnothing\}$. Function $u : \Sigma \times Term \to U$ assigns agents' utilities to every final position of the game [16]. We say that $M = \langle \mathbb{A}\mathrm{gt}, Q, \Pi, \pi, Act, d, o \rangle$ corresponds to Γ iff:

- $\mathbb{A}\mathrm{gt} = \Sigma$,
- $Q = H$,
- Π and π include propositions $(u_a \geq v)$ to emulate utilities for terminal states in the way described above,
- $Act = \mathcal{A} \cup \{nop\}$,
- $d_a(q) = \mathcal{A}(q)$ if $a = ow(q)$ and $\{nop\}$ otherwise,
- $o(q, nop, ..., \alpha, ..., nop) = q\alpha$, and
- $o(q, nop, nop, ..., nop) = q$ for $q \in Term$.

Additionally, for an ATL+I model M' that adds intentions and strategic terms to M, we define that Γ corresponds to M' iff Γ corresponds to M and $q\mathcal{I}_a\alpha$ for every $q \in Q, a \in \mathbb{A}\mathrm{gt}, \alpha \in d_a(q)$ (all choices are possibly intended). Note that for every extensive form game Γ, there is a corresponding concurrent game structure, but the reverse is not true.

Now we can show how Nash equilibrium can be specified in ATL+I, and how one can reason about outcomes of agents whose rationality is defined in terms of Nash equilibrium. As games specified by concurrent game structures are usually infinite, there are no terminal positions in these games in general. Therefore it seems reasonable to define outcomes of strategies via properties of resulting paths (courses of action) rather than single states.[5] For example, we may be satisfied if a utility value v is achieved eventually: $\Diamond(u_a \geq v)$, preserved until the end of the game: $(u_a \geq v)\mathcal{U}\mathsf{end}$ etc. To capture such subtleties, we propose the notion of T-*Nash equilibrium*, parametrized with a unary temporal operator $T = \bigcirc, \Box, \Diamond, \_\mathcal{U}\psi, \psi\mathcal{U}\_$. Thus, we have a family of equilibria now: $\bigcirc$-Nash equilibrium, $\Box$-Nash equilibrium etc. Let σ describe a collective strategy for the grand coalition $\mathbb{A}\mathrm{gt}$, and let $\sigma[a]$ be the strategic term for a's strategy in σ. Similarly, $\sigma[A]$ is the part of σ that refers to the strategy of A. We write $BR_a^T(\sigma)$ to denote the fact that strategy $\sigma[a]$ is a_i's best response to $\mathbb{A}\mathrm{gt} \setminus \{a\}$ playing $\sigma[\mathbb{A}\mathrm{gt} \setminus \{a\}]$. For example, $BR_a^{\Box}(\sigma)$ means that a cannot increase his minimal guaranteed payoff by deviating from $\sigma[a]$ unilaterally. Likewise, $BR_a^{\Diamond}(\sigma)$ says that a cannot increase his maximal guaranteed payoff (i.e. the payoff that can be obtained *eventually*

[5] The idea of assigning utilities to *runs* rather than states is not entirely new, cf. [28].

1	x, 1, 0	7	x, −3, −1
2	x, 1, 2	8	x, −3, 1
3	x, 1, 0	9	1, −3, 0
4	x, 1, 2	10	1, −3, 2
5	x, 1, −1	11	1, −3, 0
6	x, 1, 1	12	1, −3, 2

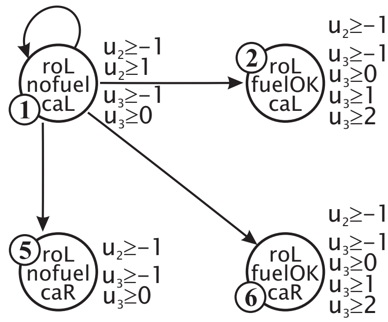

Figure 2: The rocket game: utility table and a fragment of the game structure

along *every* possible course of action) by a unilateral deviation from $\sigma[a]$. We write $NE^T(\sigma)$ to denote the fact that σ is a T-Nash equilibrium.

$$BR_a^T(\sigma) \equiv (\mathbf{str}_{\mathbb{A}\mathrm{gt}\setminus A}\sigma[\mathbb{A}\mathrm{gt}\setminus\{a\}])(\bigwedge_{v\in U}(\langle\!\langle a\rangle\!\rangle T(u_a \geq v)) \rightarrow (\mathbf{str}_a\sigma[a])\langle\!\langle\rangle\!\rangle T(u_a \geq v))$$

$$NE^T(\sigma) \equiv \bigwedge_{a\in\mathbb{A}\mathrm{gt}} BR_a^T(\sigma).$$

Proposition 8 *Let Γ be a game, and M a concurrent game structure with intentions, corresponding to Γ. Then $M, \varnothing \models NE^{\Diamond}(\sigma)$ iff σ denotes a Nash equilibrium in Γ.*

Thus, Nash equilibrium in traditional games is the special case of our temporal Nash equilibrium, in which we ask about utilities one must get eventually at the end of the game. NE^T extends this notion by focusing on temporal patterns rather than single utility values. Moreover, as concurrent game structures specify interactions that are usually infinite and may include simultaneous moves of players (as well as cycles of transitions), the concept of Nash equilibrium naturally extends to such generalized games in our definition.

Example 3 Let us consider an infinite game played by the "rocket agents" from previous examples. Suppose that the task of agent 1 is to deliver the cargo to Paris; thus, 1 gets a payoff only in the states where caP holds. Moreover, the cargo may contain some materials that can incriminate agent 2 before the French police. Thus, 2 feels very unsafe when the cargo is in Paris (outside or inside the rocket), and safe otherwise. Finally, 3 is paid a bonus when the rocket tank is full; on the other hand, he is responsible for cargo on board of the rocket, so he prefers when no cargo is loaded. The agents, cargo and rocket are initially in London. Figure 2 shows the table of utilities for the game, as well as a fragment of system M_3, that augments M_1' with propositions encoding agents' utilities. Note that, unlike for game structures corresponding to traditional game trees, there are no final states in the model, and utility values are defined for most states.

Let $carry$ denote the strategy for agent 1, in which the agent loads the cargo in states $1, 2, 5$, moves the rocket in states $4, 6$, unloads the cargo in $7, 8$ and does nothing in $3, 9, 10, 11, 12$. Moreover, $fuel$ denotes the strategy in which 3 executes $fuel_3$ in $1, 3, 5, 7, 9, 11$, and nop_3 elsewhere. Now, $M_3, 1 \models NE^{\Diamond}(\langle carry, nop, fuel\rangle)$ because $BR_1^{\Diamond}(carry, \langle nop, fuel\rangle)$ and $BR_2^{\Diamond}(nop, \langle carry, fuel\rangle)$ and $BR_3^{\Diamond}(fuel, \langle carry, nop\rangle)$ – actually, all 3 agents obtain their highest possible payoffs eventually while $\langle carry, nop, fuel\rangle$ is executed.[6] Also, $M_3, 6 \models NE^{\Box}(\langle nop, nop, nop\rangle)$: 2 and 3 are satisfied at state 6, and 1 cannot achieve $\Box \mathsf{caP}$ anyway. Thus, the system is in $\Diamond$-Nash equilibrium in state 1, and in $\Box$-Nash equilibrium in state 6. ■

Properties of rational strategies can be now verified through formulae of form $NE^T(\sigma) \wedge (\mathbf{str}_{\mathbb{A}\mathrm{gt}}\sigma)\varphi$, where φ is the property we would like to check. For example, we have that $M_3, 6 \models NE^{\Box}(\langle nop, nop, nop\rangle) \wedge (\mathbf{str}_{\mathbb{A}\mathrm{gt}}\langle nop, nop, nop\rangle)\langle\langle\rangle\rangle\Box\mathsf{caR}$.

Remark 9 Building upon the concept of Nash equilibrium, we may like to express rationality of strategies as: *"$rational_A^T(\sigma_A)$ iff there is $\sigma'_{\mathbb{A}\mathrm{gt}\setminus A}$ such that $NE^T(\sigma_A, \sigma'_{\mathbb{A}\mathrm{gt}\setminus A})$"*. In a similar way, it seems natural to reason about behavior of rational agents with sentences like *"suppose that A intend to play any strategy σ_A such that $rational_A^T(\sigma_A)$, then φ holds"*, Note that reasoning of this kind is beyond the scope of ATL+I, as the logic does not include explicit quantification over strategies yet. ■

5 Conclusions

What ATL offers, is in fact an abstraction of strategies. ATL modalities quantify over strategies in game theory-like fashion, but the strategies are hidden in the semantics: we can only specify *who* can do *what* and *when* in the object language of ATL, but we cannot tell *how* it can be done. In this paper, we propose to extend ATL with a notion of agents' intentions, and with an operator that enables addressing agents' strategies explicitly. The resulting logic, ATL+I, provides a formal language to express (and reason about) facts concerning strategies of agents in multiagent settings. We believe that the logic offers more than just a sum of its parts: counterfactual reasoning in game-like situations, dynamic logic of strategies, intention revision, rationality criteria, reasoning about rational intentions as well as relationship between intentions and goals are example issues that can be formalized and investigated with ATL+I. Thus, most of all, we see ATL+I as a potent framework for modeling and specifying systems that include multiple agents, and for discussing and verifying their properties.

[6] Note that this does *not* happen at the same moment, though.

References

[1] R. Alur, T. A. Henzinger, and O. Kupferman. Alternating-time Temporal Logic. In *Proceedings of the 38th Annual Symposium on Foundations of Computer Science (FOCS)*, pages 100–109. IEEE Computer Society Press, 1997.

[2] R. Alur, T. A. Henzinger, and O. Kupferman. Alternating-time Temporal Logic. *Lecture Notes in Computer Science*, 1536:23–60, 1998.

[3] R. Alur, T. A. Henzinger, and O. Kupferman. Alternating-time Temporal Logic. *Journal of the ACM*, 49:672–713, 2002.

[4] A. Baltag. A logic for suspicious players. *Bulletin of Economic Research*, 54(1):1–46, 2002.

[5] A. L. Blum and M. L. Furst. Fast planning through graph analysis. *Artificial Intelligence*, 90:281–300, 1997.

[6] M.E. Bratman. *Intentions, Plans, and Practical Reason*. Harvard University Press, 1987.

[7] E.M. Clarke and E.A. Emerson. Design and synthesis of synchronization skeletons using branching time temporal logic. In *Proceedings of Logics of Programs Workshop*, volume 131 of *Lecture Notes in Computer Science*, pages 52–71, 1981.

[8] P.R. Cohen and H.J. Levesque. Intention is choice with commitment. *Artificial Intelligence*, 42:213–261, 1990.

[9] E. A. Emerson. Temporal and modal logic. In J. van Leeuwen, editor, *Handbook of Theoretical Computer Science*, volume B, pages 995–1072. Elsevier Science Publishers, 1990.

[10] E.A. Emerson and J.Y. Halpern. "sometimes" and "not never" revisited: On branching versus linear time temporal logic. *Journal of the ACM*, 33(1):151–178, 1986.

[11] F. Giunchiglia and P. Traverso. Planning as model checking. In *ECP*, pages 1–20, 1999.

[12] D. Harel, D. Kozen, and J. Tiuryn. *Dynamic Logic*. MIT Press, 2000.

[13] W. Jamroga. Strategic planning through model checking of ATL formulae. In L. Rutkowski et al., editor, *Artificial Intelligence and Soft Computing: Proceedings of ICAISC'04*, volume 3070 of *Lecture Notes in Computer Science*, pages 879–884. Springer Verlag, 2004.

[14] J.-J.Ch. Meyer. A different approach to deontic logic: Deontic logic viewed as a variant of dynamic logic. *Notre Dame Journal of Formal Logic*, 29(1):109–136, 1988.

[15] J.-J.Ch. Meyer and R.J. Wieringa. Deontic logic: A concise overview. In J.-J.Ch. Meyer and R.J. Wieringa, editors, *Deontic Logic in Computer Science: Normative System Specification*, pages 3–16. John Wiley & Sons, 1993.

[16] M. Osborne and A. Rubinstein. *A Course in Game Theory*. MIT Press, 1994.

[17] M. Pollack. The uses of plans. *Artificial Intelligence*, 57(1):43–68, 1992.

[18] A.S. Rao and M.P. Georgeff. Modeling rational agents within a BDI-architecture. In *Proceedings of the 2nd International Conference on Principles of Knowledge Representation and Reasoning*, pages 473–484, 1991.

[19] A.S. Rao and M.P. Georgeff. Formal models and decision procedures for multi-agent systems. Technical Report 61, Australian Artificial Intelligence Institute, 1995.

[20] P. Y. Schobbens. Alternating-time logic with imperfect recall. *Electronic Notes in Theoretical Computer Science*, 85(2), 2004.

[21] R. Stalnaker. Knowledge, belief and counterfactual reasoning in games. *Economics and Philosophy*, 12:133–163, 1996.

[22] W. van der Hoek, W. Jamroga, and M. Wooldridge. A logic for strategic reasoning. In *Proceedings of AAMAS'05*. 2005.

[23] W. van der Hoek, M. Roberts, and M. Wooldridge. Social laws in alternating time: Effectiveness, feasibility and synthesis. *Synthese*, 2005.

[24] S. van Otterloo and G. Jonker. On Epistemic Temporal Strategic Logic. In *Proceedings of LCMAS*, pages 35–45, 2004.

[25] S. van Otterloo, W. van der Hoek, and M. Wooldridge. Preferences in game logics. In *Proceedings of AAMAS-04*, 2004.

[26] G.H. von Wright. Deontic logic. *Mind*, 60:1–15, 1951.

[27] M. Wooldridge. *Reasoning about Rational Agents*. MIT Press : Cambridge, Mass, 2000.

[28] M. Wooldridge. *An Introduction to Multi Agent Systems*. John Wiley & Sons, 2002.

Impressum

Publisher: Institut für Informatik, Technische Universität Clausthal
Julius-Albert Str. 4, 38678 Clausthal-Zellerfeld, Germany
Editor of the series: Jürgen Dix
Technical editor: Wojciech Jamroga
Contact: wjamroga@in.tu-clausthal.de
URL: http://www.in.tu-clausthal.de/~wjamroga/techreports/
ISSN: 1860-8477

The IfI Review Board